A triple-slot active reflectarray cell using a ferroelectric capacitor

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***Abstract*—A tunable reflectarray phase-shifting cell, designed for a resonance frequency of 5.5 GHz, is presented. The cell is based on a triple-slot topology and loaded by a ferroelectric thin film capacitor with 60% tunability under 400 kV/cm bias electric field. The use of three slots allows reducing the losses and increasing the bandwidth of the cell. The cell provides 270 degrees of phase range with a maximum of 6 dB loss in the band.**

***Index Terms*—Ferroelectric, reflectarray, thin film, tunability.**

I. Introduction

Planar reflectarrays are widely studied because they combine the advantages of printed array antennas and reflector antennas [1]. Active cells enable reconfigurable reflectarrays whose radiating beam can be steered or shaped dynamically. Active cells usually derive from passive topologies in which electronic devices are integrated in order to control the desired phase-shift [2], [3]. Advanced tunable materials like Liquid Crystals [4] or ferroelectrics [5] can also be used. Ferroelectric materials have the advantage of no bias current, which may considerably reduce power consumption.

Most passive and active cells are based on resonance phenomena to obtain the appropriate phase range. Those kinds of cells may exhibit sharp resonances which cause a narrow bandwidth and significant losses. To reduce the losses and increase the bandwidth, multiple-resonator cells have been used with various topologies such as stacked patches [6], coupled dipoles [4] or coupled slots [7].

In [8], the principle of a ferroelectric-loaded slot for the realization of a reconfigurable cell has been demonstrated. However, this cell exhibits significant losses due to its sharp resonance. An improved cell using three slots with a single capacitive load has been proposed in [7] and validated by simulation. In the present paper we propose to assess its performance when a realistic technological process is considered for achieving the tunable capacitive loading.

II. Ferroelectric Material

Ferroelectrics are non-linear materials well known for their high and tunable relative permittivity. They can be used in different microwave devices such as phase-shifters, filters, antennas or reflectarray cells. In the proposed device, Barium-Strontium-Titanate (BST) has been chosen because of its relatively low dielectric losses and high tunability. Moreover BST has a low coercive field, which considerably reduces the hysteresis effect and thus simplifies the electric command. The films were elaborated on alumina substrates by chemical solution deposition [9]. A one-percent manganese-doping has been used in order to reduce low frequency leakage currents and to prevent from breakdown while biasing the material [10]. Dielectric characterization has been performed using a technique described in [11]. At 5 GHz, the thin films have a relative permittivity of 350, a tunability of 60% under 400 kV/cm and a $\tan\delta$ = 0.02. Details of the material characterization shall be published elsewhere.

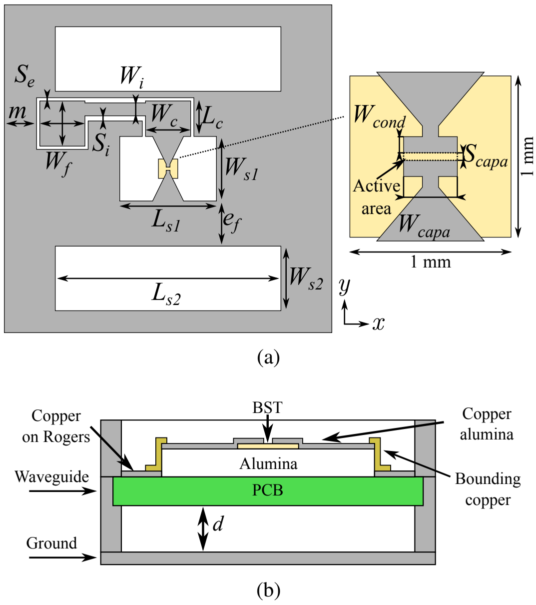

Figure 1. Topology of the proposed cell and zoom on the capacitor region (top view) (a). The dielectric stack in the waveguide (side view) (b). L_{s1} = 8 mm ; L_{s2} = 18 mm ; W_{s1} = W_{s2} = 5 mm ; e_f = 3.5 mm ; W_c = 4 mm ; L_c = 3 mm ; W_e = 30 µm ; m = 2.5 mm ; W_i = 1 mm ; S_i = 0.4 mm ; S_e = W_{cond} = 30 µm ; W_{capa} = 190 µm ; S_{capa} = 7 µm ; d = 15.7 mm.

III. Cell Design

The proposed unit-cell consists of three slots in a ground plane as shown in Fig. 1a and is designed for operation at 5.5 GHz. Both external slots have the same length in order to preserve the cell symmetry. The presence of these slots allows reducing the frequency dispersion and losses by providing a second resonance. As demonstrated in [7], the electrical length

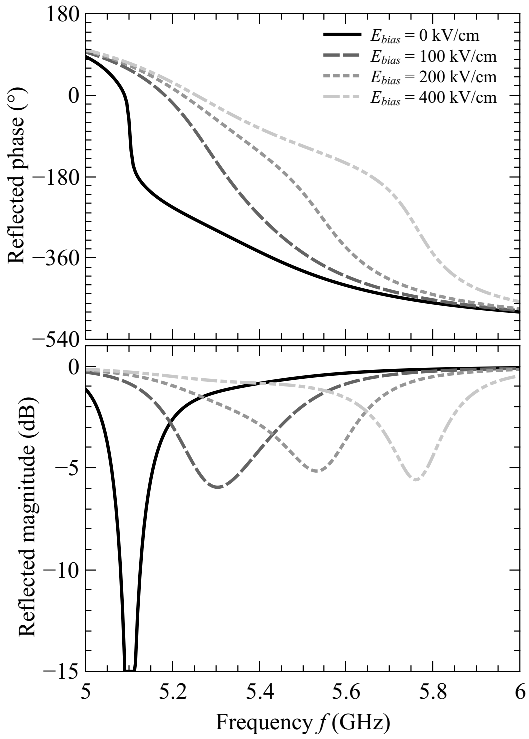

Figure 2. Simulated reflection coefficient (phase and magnitude) of the proposed cell for different applied bias field.

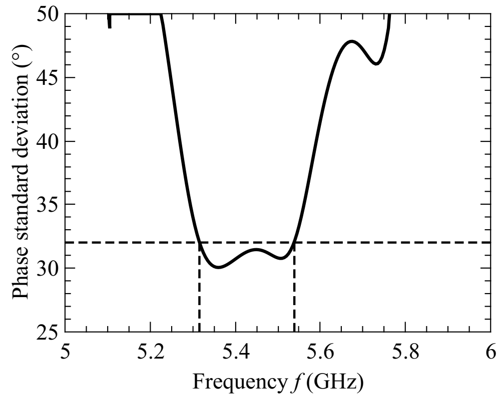

Figure 3. Phase standard deviation computed from 4 chosen states of the proposed cell.

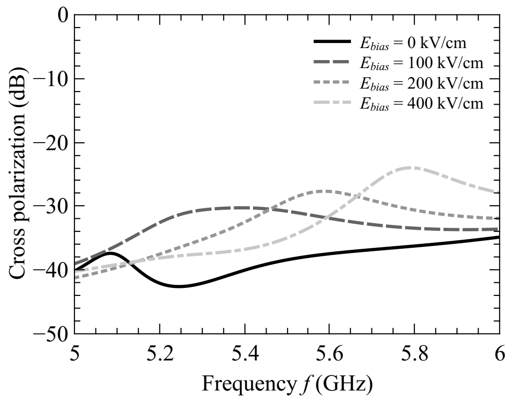

Figure 4. Simulated cross polarization of the proposed cell for different applied bias field.

of the central slot controls the phase-shift of the reflected wave. By loading this slot with a tunable capacitor, it is possible to change its electrical length and thus the phase-shift dynamically.

For the sake of simplicity (regarding measurement), the cell is embedded in a 35×35 mm^2 square metallic waveguide. Fig. 1b shows the details of the used dielectric stack. The alumina substrate (25.4×25.4 mm^2, thickness 508 µm and ε_r = 9.8) with the integrated BST thin film is reported on a printed circuit board (PCB, ε_r = 2.17, $\tan\delta$ = 9.10^{-4} and thickness 1.6 mm) which is mounted 15.7 mm above the ground plane ending the metallic waveguide. In order to reduce the dielectric losses, the ferroelectric material has been limited by wet etching to only a 1×1 mm^2 surface for hosting the capacitor. The thickness of the ferroelectric film is 1 µm. The electrode metallization (1.4 µm thick) is realized by sputtering copper and patterning with a classical photolithography process.

The widths and the lengths of the slots have been optimized for obtaining as flat as possible phase states (in order to reduce losses) and a sufficient phase range with available tunability of the BST film. The distance between the slots e_f controls the mutual coupling and has been chosen to minimize the phase slope while preserving enough space for the biasing circuit.

The tunable capacitor consists of two coplanar electrodes deposed on the ferroelectric film which are separated by a 7 µm wide gap S_{capa} (zoom of Fig. 1a). The biasing circuit can be seen in Fig. 1a. Isolation of the biased electrode from the ground is done by a narrow gap (S_e width). In addition, a low-pass distributed filter is necessary for improving the decoupling between the DC bias and the RF signal. It consists of an inductive line (width W_i and length L_i) followed by a capacitive line (width W_f and length L_c).

IV. Simulation

The simulations of a unit cell have been performed using the waveguide approach with HFSS^{TM} commercial software. The section of the waveguide is 35×35mm^2 and the excited mode is the TE_{10} mode (according to Fig. 1a). The relative permittivity of the active material has been varied from 350 to 175, which corresponds to a maximum applied bias field of 400 kV/cm. The different simulations are reported in Fig. 2. The use of multiple resonators is clearly visible because the phase-shift has a quite smooth evolution versus frequency and the phase-shift is provided in a wide band, contrary to what is obtained with single-resonator cells [8]. The losses are still quite high (up to 6 dB) but lower than those reported in [5], [8] for similar materials.

The bandwidth of the cell has been estimated by choosing 4 states (corresponding to 4 values of the electric bias field) and computing the standard phase deviation [12]. The obtained

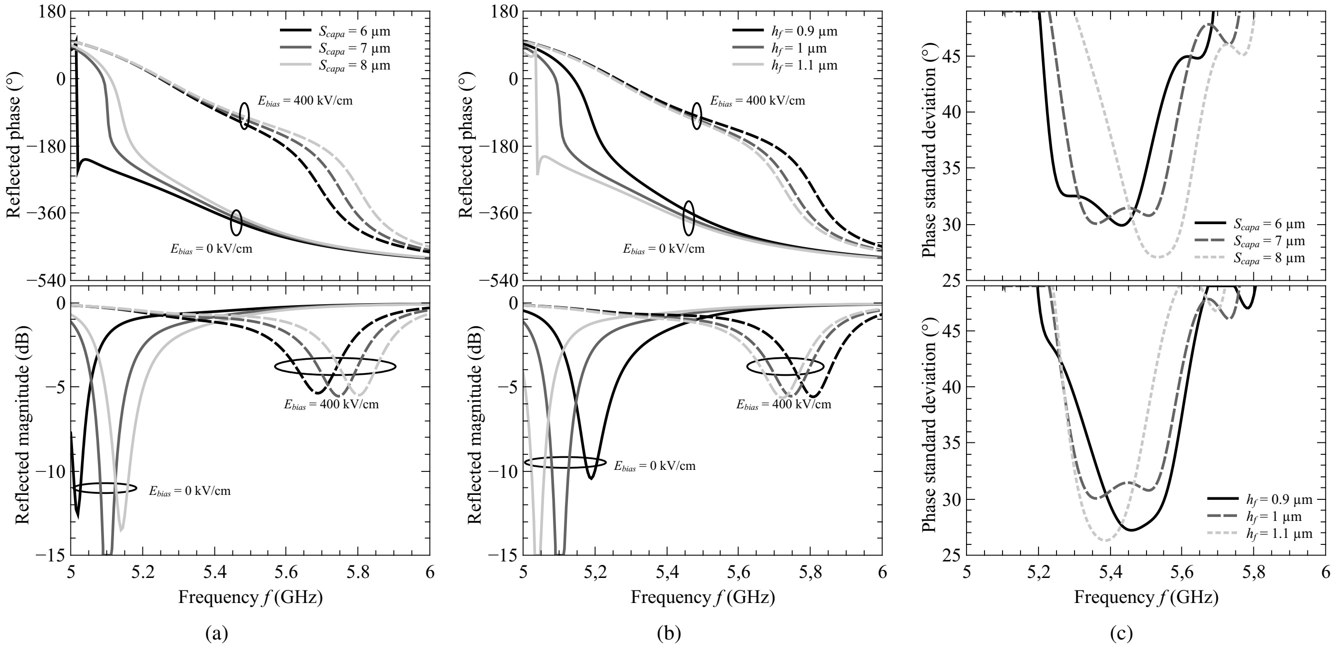

Figure 5. Simulated reflection coefficient (phase and magnitude) of the proposed cell for different gap widths of the active capacitor S_{capa} (a) and different thicknesses of the material of the active capacitor h_f (b). Phase standard deviation computed with 4 chosen states for different width of the gap S_{capa} (top) and for different thicknesses h_f (bottom).

value is less than 32° within a 220 MHz band (Fig. 3) which corresponds to a 1.70 bit phase-shifter.

As the cell is not symmetrical (due to the biasing circuit), the cross polarization has also been verified. It remains below −28 dB in the considered band (Fig. 4), which indicates that the addition of the biasing circuit does not extensively disturb the radiation.

V. Sensitivity study

The sensitivity to the physical dimensions of the cell has been investigated in simulation. The most critical parameters are the gap between the two electrodes of the active capacitor S_{capa} and the thickness of the ferroelectric material h_f.

The value of the gap has been varied in simulation from 6 µm to 8 µm and the results are presented Fig. 5a. This corresponds to the uncertainty of the dimensions resulting from the etching process of copper. A variation of the gap introduces a frequency shift; this is logical because the gap controls the capacitance which loads the central slot. The thickness has also been varied from 0.9 µm to 1.1 µm and the results are reported Fig. 5b. The influence on the phase response is quite similar; indeed, this thickness controls the contribution of the active material to the effective permittivity in the capacitor and thus the capacitance itself. For the different variations of both parameters, the accessible phase range stays close to 270°.

To complete the sensitivity study, the phase standard deviation has been computed for the different values of h_f and S_{capa}, the results are shown Fig. 5c. The uncertainty is responsible for a slight variation of the bandwidth and of the central frequency.

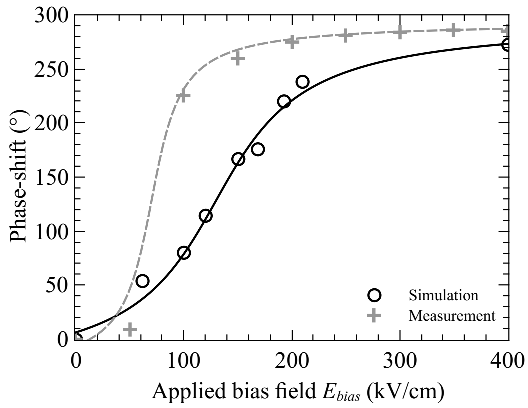

Figure 6. Simulated and measured phase-shifts provided by the proposed cell as a function of the bias field applied on the material.

VI. Measurement

The proposed cell has been measured in a 35×35 mm^2 square metallic waveguide fed with a standard WR137 rectangular waveguide [7]. The reference plane is set on top of the alumina substrate and three offset short-circuits are used for calibration [13].

The simulated and measured phase-shift values as a function of the applied bias field are reported in Fig. 6. The maximum phase-shift and the overall phase range obtained in measurement are close to the simulated ones. This shows that the ferroelectric material is promising to realize reconfigurable cells. Nevertheless, the evolution with the applied bias field is sharper in measurement. This difference comes with higher losses than expected. The conductivity of the copper deposited by sputtering has been measured and the value is $\sigma = 2.10^7$ S.m^{-1}, which is much smaller than the bulk value and could explain these differences.

VII. Conclusion

An active triple-slot phase-shifting cell is presented. The use of multiple-resonators reduces the losses (less than 6 dB in simulation) and increases the bandwidth of the cell as compared to a single-slot topology. The cell provides a 270° phase range with a 60% tunability of the material (corresponding to a maximum applied bias field of 400 kV/cm in the case of the used BST thin film). This allows to easily derive 4 uniformly-distributed phase states. The effect of the biasing lines has also been assessed and the impact on the cross-polarization is negligible.

The sensitivity of the cell to the gap between the plates of the ferroelectric capacitor and to the thickness of the active material has been evaluated in simulation and is moderate.

The maximum phase-shifts obtained in measurement and in simulation are very close to one another. Work is underway to increase the conductivity of the deposited copper and thus to obtain a smoother variation of the phase-shift with the applied electric field.

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